

A Field-deployed 810 GHz Receiver Incorporating a Superconducting Mixer Developed for Herschel Space Telescope and a SiGe Low Noise Amplifier

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Abstract — We have constructed an 810 GHz receiver system incorporating a HIFI Band-3 superconductor-insulator-superconductor (SIS) mixer developed for Herschel space observatory and a wide-band SiGe low noise amplifier (LNA) designed at Caltech. The instrument is currently installed at the RLT telescope (elevation 5500 m) in northern Chile. Hot/cold (280K/72K) load measurements performed at the telescope yield noise temperatures of 225 K (Y-factor = 1.7) including receiver optics. First-light observations indicate that the receiver is highly sensitive and functions stably. We present details of the receiver system, its performance at the telescope, and first-light observations with a Herschel mixer.

Index Terms — IF amplifiers, submillimeter wave measurements, radio astronomy, submillimeter wave receivers, submillimeter wave spectroscopy, superconductor insulator superconductor mixers.

I. INTRODUCTION

A key goal of upcoming space-based and airborne missions is improving our understanding of the structure of the Galactic interstellar medium (ISM) and the life cycle of interstellar clouds as a stepping stone to understanding the internal evolution of galaxies. Through the efforts of many researchers, the far-infrared (FIR) and terahertz (THz) atmospheric window, harboring important spectral line probes of molecular clouds and star formation, including high-J CO lines and N+ at around 1.3 and 1.5 THz, is becoming accessible with unprecedented sensitivity and resolution capabilities [1]-[4]. Complementary observations of key species in the 800 GHz atmospheric window are needed over large spatial scales (multiple square degrees) both for a more complete picture of the lifecycle of the ISM and for producing finder charts enabling the efficient use of new and upcoming THz observatories.

We have constructed and deployed (December 2008) an ultra-sensitive 810 GHz heterodyne receiver system on the RLT telescope in northern Chile [5] capable of making these much needed observations. At the heart of the receiver is an 800 GHz SIS mixer developed for Band-3 of the HIFI instrument for the Herschel Space Telescope [6, 7] to be launched in April 2009. The mixer unit is connected to a wide-band SiGe LNA designed at Caltech [8]; the first of its

kind to be used in a submillimeter (submm) receiver functioning at a telescope. The system operates with a 1-2 GHz IF capable of simultaneously observing important spectroscopic probes of star formation including neutral atomic carbon $^{12}\text{C}^0$ and $^{13}\text{C}^0$ $J = 2-1$ and carbon monoxide CO $J = 7-6$ lines near 809 GHz and 806 GHz, respectively. Equipped with a spectrometer affording high spectral resolution (< 0.5 km/s) and coupled with a moderate telescope beamsizes of 1.9' at 810 GHz, this new RLT receiver system can provide an important complement, including finder charts and large-scale surveys, to upcoming THz observatories like Herschel, SOFIA, and STO. We present details of the receiver system, including results and performance at the RLT, and first-light observations obtained with a Herschel mixer.

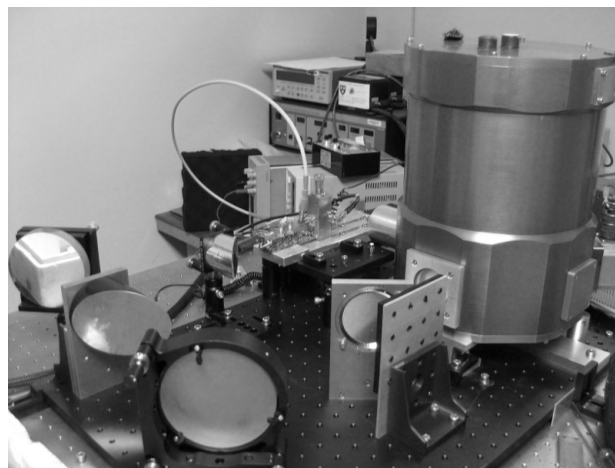


Fig. 1. Layout of the 810 GHz receiver system: view of receiver system operating in the laboratory complete with LO unit and all optics needed to couple the beam to the RLT.

II. OVERVIEW OF THE RECEIVER SYSTEM

The mixer assembly is a pre-flight spare for Band-3 of the HIFI instrument. It is specified to operate between 800 and 960 GHz. This mixer is projected to achieve a noise temperature of about 150 K at 800 GHz in the spacecraft

under typical operating conditions. The details of the design and construction of the mixer is described in [9]. We have installed the mixer block in a liquid helium cooled cryostat equipped with an anti-reflection coated quartz vacuum window and infra-red blocking filters. Two off-axis parabolic mirrors, one placed inside the cryostat and a second one mounted outside the cryostat couple the beam emerging from the corrugated feed of the mixer block to the main telescope optics. The optical design was carried out with the use of the ZEMAX software package. The layout of our instrument is shown in Fig. 1.

The mixer assembly contains an integral bias-tee. It is connected to a SiGe IF amplifier [8] by a 100 mm long coaxial cable. This is the first use of a SiGe amplifier in a submm receiver system deployed on a telescope. Housed in a small package of about 3 cm x 2 cm x 1 cm, it has very low noise from 0.2 GHz to 4 GHz in addition to low power dissipation. Unlike most cryogenic HEMT amplifiers which require a servo loop to adjust the gate voltage so as to maintain a constant drain current and hence a stable gain, this SiGe amplifier can simply be operated with a fixed drain voltage. We have chosen a drain voltage of 1.4 V, which represents a compromise between several considerations (see Fig. 2). At lower bias voltage, the power dissipation is reduced and the gain flatness is improved. However, by increasing the bias voltage, higher gain and a lower noise temperature can be obtained. At our operating voltage, the power dissipation is only about 7 mW for a noise temperature of close to 4.5 K over the 1-2 GHz IF range. The gain of the amplifier is 38 dB at 1 GHz, decreasing to 36 dB at 2 GHz and to 33 dB at 4 GHz. The gain slope is further accentuated by the 1 meter long stainless steel coaxial cable connecting the amplifier to the output port of the cryostat. Gain equalization is achieved using the external IF processor resulting in a 2.5 dB peak-to-peak ripple in the power output spectrum.

The local oscillator (LO) unit used in this system incorporates a fixed-tuned planar diode doubler cascade developed by Jet Propulsion Laboratory for the Herschel space mission [10, 11]. The primary source is a Gunn oscillator operating at around 101 GHz. After passing through a compact coupler with an integrated harmonic mixer diode for phase-locking purposes, the output power of the Gunn oscillator is amplified by 2 stages of a W-band power amplifier to about 200 mW. This power drives a cascade of 3 stages of frequency doublers to yield ~ 0.2 mW of radiated output power at 808 GHz. An off-axis mirror couples the LO power to the mixer through a wire grid polarizer oriented to reflect a small fraction of the LO output power which can be controlled by varying the drain bias voltage on the power amplifiers.

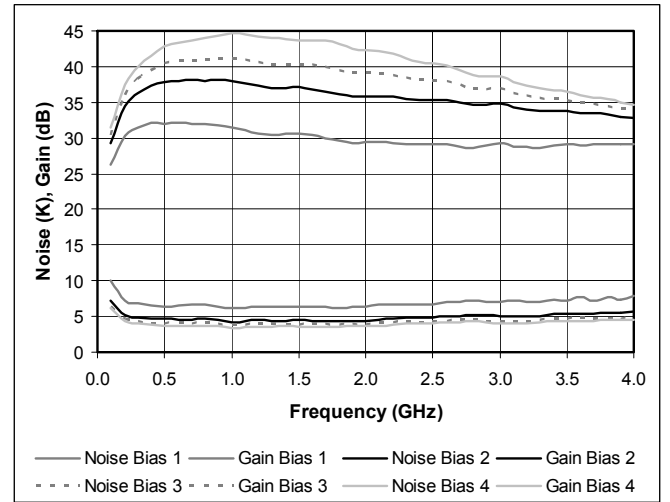


Fig. 2. Gain (top 4 curves) and noise (bottom 4 curves) characteristics of the SiGe LNA operated at 20 K with different drain voltages (cases 1-4 correspond to 1.2 V, 1.4 V, 1.6 V, and 2 V drain voltage). For operations with the 810 GHz receiver, a drain voltage = 1.4 V was used.

The purpose of the receiver is achieving simultaneous observations of three astronomically significant lines including neutral atomic carbon and carbon monoxide lines at around 809 GHz and 806 GHz, respectively. For this reason, the SIS mixer is operated in a double-side-band mode at a fixed LO frequency of about 808 GHz. Using a 1-2 GHz intermediate frequency (IF), the carbon lines appear in the upper-side-band, and the CO line appears in the lower-side-band. A digital autocorrelator made by Spaceborne, Inc. with 1024 channels and a maximum bandwidth of 1 GHz was used as a backend spectrometer, resulting in a channel width of 1 MHz and a corresponding spectral resolution of 0.4 km/s at 810 GHz.

III. RESULTS

A. Lab Measurements and Characterization

The SIS mixer operates best with a magnetic field which delivers 3 quanta of magnetic flux to the junction. This corresponds to a coil current of around 15 mA. At higher field strength, the quality of the SIS device is visibly degraded while at lower levels, receiver stability is poor. The optimal operating bias point of the mixer is found to be at 2.1 mV and 50 μ A. Since a resistor network for ESD protection is built into the mixer block, the actual bias current is probably around 20 μ A. To achieve this operating condition, we used a grid angle of about 5 degrees in the LO coupling wire grid polarizer, which is equivalent to about 1.5% coupling and results in minimal loss in the signal beam. Even at this low coupling level, the LO unit does not need to be operated at full power. Standard hot/cold load sensitivity measurements were

performed at the input pupil to the complete receiver system. A Y-factor of 1.7 was recorded, which translates into a receiver system noise temperature of 235 K (Rayleigh-Jeans temperature), averaged over the entire IF pass-band. This sensitivity compares favorably to the lab measurements reported by the HIFI Band-3 development team [9] given that our bath temperature is at 4.2 K and the entire optics train is included in our measurement.

Before installation of the warm optical components, the beam emerging from the cryostat was mapped both in amplitude and phase by a near-field scanner. Adjustments were made so that the axis of the measured beam coincided with the normal to the center of the cryostat window. Then the warm optical components were positioned after careful optical alignment. Finally, the receiver beam profile at the input pupil of the receiver system was measured for final adjustment and verification. This two-step radio/optical alignment procedure was introduced in the deployment of a 1.5 THz superconducting receiver [12] but this work confirms the usefulness and validity of this method by the reproducibility and validity of the near-field measurements.

B. Performance at the Telescope

The RLT telescope is located 40 km north of the ALMA site in northern Chile at an elevation of 5525 m, one of the best ground-based sites for terahertz astronomy with atmospheric transmission as high as 50% above 1 THz [1]. A Fourier Transform Spectrometer (FTS) is also located at the site and operates continuously, providing measurements of sky brightness to determine atmospheric opacity over the 350 GHz – 3 THz range [13] and calibration information for RLT spectroscopic observations. The telescope primary mirror is 80 cm in diameter, resulting in a $\sim 1.9'$ beam at 800 GHz. The excellent observing conditions and modest beamsizes make this telescope well suited to conducting large-scale surveys in the 800 GHz atmospheric window. To this end, the SIS receiver system described in this work was deployed to the RLT in early December 2008 and began its first observing campaign.

Fig. 3 shows receiver response measured at the RLT, including plots of mixer current vs. bias voltage with and without the local oscillator signal (pumped and unpumped IV curves) and receiver output power as a function of bias voltage for ambient temperature (280 K) and liquid nitrogen (72 K) blackbody loads (PV hot/cold curves) positioned in front of the cryostat window. Optimal receiver response was achieved at a mixer bias of 2.3 mV and 55 μ A, yielding a 225 K ($Y = 1.7$) receiver noise temperature at 808 GHz, an improvement of 10 K over lab performance and a factor of 5 better than noise levels achieved with the 800 GHz HEB receiver that this system replaced. The weather during the December 2008 observing campaign was overall very good, with 40%

transmission typical in the 800 GHz atmospheric window throughout the run. First light observations made with the new SIS receiver system toward OMC1 indicate that the receiver is very sensitive and functioning stably (see Fig. 4).

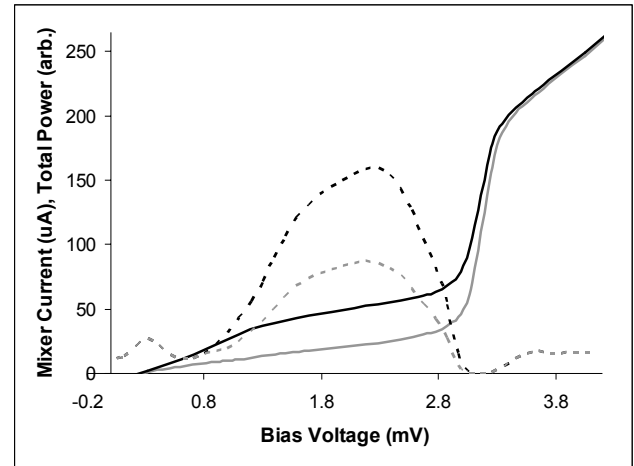


Fig.3. Performance at 808 GHz the telescope, including pumped (solid, black) and unpumped (solid, gray) IV curves and hot (dashed, black) / cold (dashed, gray) total power measurements (PV curves; note that total power is in arbitrary units, arb.) Optimal performance ($Y = 1.7$) was achieved at a mixer bias of 2.3 mV and 55 μ A, resulting in a receiver noise temperature of 225 K.

This spectrum represents a total on-source integration time of 1.5 minutes and clearly shows both CO $J = 7-6$ and weaker neutral carbon line with a high signal-to-noise (S/N) ratio, ~ 6 at the $^{12}\text{C}^0$ line center and greater than 10 in the CO line wings. The resolution of this spectrum is 0.4 km/s, adequate for resolving features in complex line profiles, enabling multiple clouds along the line of sight to be distinguished and disentangling signatures of bulk gas motions, such as rotation and outflow.

IV. CONCLUSION

We have constructed and deployed an 810 GHz receiver system incorporating a HIFI Band-3 SIS mixer developed for Herschel and a wide-band SiGe LNA to the RLT telescope (elevation 5500 m) in northern Chile. Laboratory measurements indicate that receiver performance is comparable to measurements reported by the HIFI Band-3 team and the receiver sensitivity achieved at the telescope is slightly improved, resulting in noise temperatures of 225 K ($Y = 1.7$) measured at the cryostat window. We present first-light observations with a Herschel Band-3 type mixer at a telescope and the results indicate that the 810 GHz SIS receiver system is very sensitive and functions stably. The location of the RLT and its modest primary beamsizes at 800 GHz coupled with the sensitivity of this new receiver system and high spectral resolution capabilities add to its appeal as a survey instrument. Our team is embarking on a CO/ C^0 selective

survey of molecular clouds in the Galactic plane, providing finder charts enabling the most efficient use of new terahertz facilities including Herschel and an important complement to planned C+ and N+ surveys with STO, a balloon-borne spectroscopic terahertz mission [14] in which members of our team are involved.

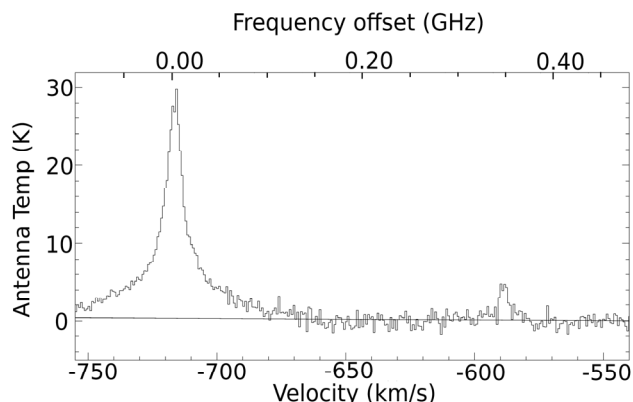


Fig. 4. Spectrum showing CO $J = 7-6$ (left, LSB) and $^{12}\text{C}^0 J = 2-1$ (right, USB) toward OMC1 made with the 810 GHz SIS receiver at the RLT during good weather conditions (40% transmission in 800 GHz window). Axes show observed source antenna temperature (K) as a function of frequency offset from the CO line center (GHz), top, and velocity (km/s), bottom. The LO frequency was changed to verify the identity of these lines. Total on source integration time is 1.5 minutes. These are first light observations for a Herschel Band-3 type mixer at a telescope.

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